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ELECTRICAL LOSSES AND RESISTANCE OF CRYOGENIC INDUCTORS WITH CONSIDERATION OF THE EFFECT OF MAGNETORESISTANCE

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A semigraphical method of calculating the electrical losses and resistance of round induction coils made of especially high purity metals (hyperconductors) - aluminum, beryllium, copper - with cryogenic cooling was developed. The peculiarity of the calculation is that it considers the effect of magnetoresistance. It uses the experimental values of the specific electrical resistance of the metals depending on the value of the induction of the transverse magnetic field at a constant low temperature. The experimental data are approximated by polynomials.

Calculated formulae are given, and graphic dependences are illustrated. 6 illustrations, 1 table, 6 references. pp. 72-77.

Along with superconductors, in order to raise the technicoeconcmic indices of electrical devices, it is expedient to use hyperconductors - especially high purity metals - with cryogenic cooling. The strong magnetic field inductors created with them are used in power engineering and physical equipment [1-3], and the use of hyperconductors in LEP [electric power transmission line] is being considered [4]. At low (cryogenic) temepratures, the specific resistance of hyperconductors is several orders of magnitude lower than at 293 K [1, 4]. The effect of transverse (or longitudinal) magnetic fields increases

the specific resistance because of the magnetic-resistive effect [1]. In general, the dependence of the resistance on the magnetic field induction is nonlinear and is typically manifested during deep cooling. For individual pure metals (Al, Na), we see a decrease in the slope of this dependence - "saturation" - at particular values of the induction and temperature. The calculation of the active resistance and losses of a cryogenic inductor must be made with consideration of the indicated factors. At present, the use of pure aluminum cooled tc the temperature of liquid hydrogen is promising. It is interesting to calculate a cryogenic inductor based on other metals: beryllium, copper, etc. For beryllium, for example, it is expedient to use liquid nitrogen for cooling; this is much simpler than using hydrogen cooling. Copper is used as a stabilizing base in superconducting systems.

We will consider a method of determining the electrical losses and resistance of a coil with a rectangular cross section in the meridional plane with consideration of the effect of magnetoresistance caused by the transverse plane meridional field of the coil. The specific details of the calculation include an essentially nonuniform distribution (within the limits of the transverse cross section) of the radial B_r and axial B_z induction components. The temperature field inside the winding is considered to be uniform. This condition is considered to be feasible with the appropriate selection of the temperature conditions - a large enough number of cooling channels, a large coolant flow rate, a moderate current density.

We will point out that the presence of local heating points lowers the overall efficiency of the inductor, while at high current densities it can lead to the uncontrollable avalance-like spreading of a region with an inadmissible temperature and the subsequent destruction of the solenoid. The strict substantiation of the selection of the cooling conditions and the current density is the subject of a separate problem of heat conductivity and heat transfer in a cryogenic inductor.

The original system for the calculated expressions contains the

following relationships:

electrical losses

$$P = 2\pi \int_{R_B}^{R_H}\int_{0}^{b} \rho j_\varphi^2 r\,dr\,dz, \tag{1}$$

electrical resistance

$$R = PI^{-2}, \tag{2}$$

and the dependence of the specific electrical resistance ρ on the modulus of the induction vector B and temperature T

$$\rho = \rho_0 + \sum_{i=1}^{n} A_i(T)\, B^{\nu_i(T)}. \tag{3}$$

Here R_B, R_H, b - the internal and external radii of the coil cross section and its width (the axial coordinate of the end); I, j_φ - the current and current density (the azimuthal value is used); ρ_0 - the specific resistance at B = 0; $A_i(T)$, $\nu_i(T)$ - the coefficients and exponents of the polynomial terms which depend on the inductor conductor material at a fixed temperature. The function $\rho(B, T)$ is taken in the form of a generalized polynomial (3).

The substitution of (3) in (1) gives us

$$P = 2\pi \int_{R_B}^{R_H}\int_{0}^{b} \rho_0 j_\varphi^2 r\,dz\,dr + 2\pi \sum_{i=1}^{n} A_i(T) \int_{R_B}^{R_H}\int_{0}^{b} B^{\nu_i} j_\varphi^2 r\,dz\,dr. \tag{4}$$

For the case of a constant averaged over the cross section of the current density $j_\varphi = Iw/S$ (w, S - the number of successively connected turns and the transverse cross section of the coil), based on (2), (4), we have

$$P = j_\varphi^2 \rho_0 V k_3^{-1} + 2\pi j_\varphi^2 R_B^3 k_3^{-1} \sum_{i=1}^{n} A_i(T) (\mu_0 j_\varphi R_B)^{\nu_i} \theta_i. \tag{5}$$

$$R = u^2\rho_0 V k_3^{-1} S^{-2} + 2\pi w^2 R_s^3 k_3^{-1} S^{-2} \sum_{i=1}^{n} A_i(T)(\mu_0 j_s R_s)^{\gamma_i}\theta_i. \quad (6)$$

Here $V = \pi[R_н^2 - R_s^2]b$ is the volume of the coil, k_3 - the pulse duty factor, $\mu_0 = 4\pi \cdot 10^{-7}$ H/m.

The coefficients θ_i in (5), (6) are determined by the relationship

$$\theta_i = \int_1^{\mathring{R}_н} \int_0^{\mathring{b}} \mathring{r}\mathring{B}^{\gamma_i} d\mathring{z} d\mathring{r}. \quad (7)$$

The relative value of the induction $\mathring{B} = \sqrt{\mathring{B}_r^2 - \mathring{B}_z^2}$,

$$\mathring{B}_r = \frac{1}{4\pi} \int_{\mathring{V}} \frac{(\mathring{z} - \mathring{\zeta})\cos\varphi}{\mathring{a}^3} d\mathring{V}, \quad (8)$$

$$\mathring{B}_z = \frac{1}{4\pi} \int_{\mathring{V}} \frac{(\mathring{\xi} - \mathring{r}\cos\varphi)}{\mathring{a}^3} d\mathring{V}, \quad (9)$$

where $\mathring{a} = [\mathring{r}^2 + \mathring{\xi}^2 - 2\mathring{r}\mathring{\xi}\cos\varphi + (\mathring{z} - \mathring{\zeta})^2]^{0,5}$ - the distance from the observation point $(\mathring{r}, \mathring{z})$ to the elementary volume $d\mathring{V} = \mathring{\xi} d\mathring{\xi} d\mathring{\zeta} d\varphi$, whereupon $\mathring{\xi} = \xi/R_s$, $\mathring{r} = r/R_s$, $\mathring{\zeta} = \zeta/R_s$, $\mathring{z} = z/R_s$ - the radial and axial coordinates, $\mathring{R}_н = R_н/R_s$, $\mathring{b} = b/R_s$.

The dimensionless analogs $\mathring{B}_r = B_r/\mu_0 j_s R_s \sim$ idem, $\mathring{B}_z = B_z/\mu_0 j_s R_s \sim$ idem of the induction components B_r, B_z of geometrically similar coils are identical at the similar points $\mathring{r} =$ const, $\mathring{z} =$ const.

Integrating (8), (9) with respect to $\mathring{\xi}$ and $\mathring{\zeta}$ we obtain the calculated expressions for $\mathring{B}_r$, $\mathring{B}_z$:

$$\mathring{B}_r = \frac{1}{2\pi}\left\{\frac{\pi\mathring{r}}{2}\ln\left[\mathring{\xi} + \mathring{r} + \sqrt{(\mathring{\xi} + \mathring{r})^2 + (\mathring{z} - \mathring{\zeta})^2}\right] + \int_0^{\pi}\left[\mathring{a}\cos\varphi - \frac{\mathring{r}^2(\mathring{a} + \mathring{\xi})(\varphi + 0,5\sin 2\varphi)\sin\varphi}{2\mathring{a}(\mathring{\xi} - \mathring{r}\cos\varphi + \mathring{a})}\right]d\varphi\right\}\Bigg|_0^{\mathring{\zeta}=\mathring{b}}\Bigg|_1^{\mathring{\xi}=\mathring{R}_н}, \quad (10)$$

$$\mathring{B}_z = -\frac{1}{2\pi}\int_0^{\pi}\left\{\frac{\mathring{\xi}\mathring{r}^2\sin^2\varphi}{\mathring{a}(\mathring{z} - \mathring{\zeta} + \mathring{a})} + (\mathring{z} - \mathring{\zeta})\ln(\mathring{\xi} - \mathring{r}\cos\varphi + \mathring{a}) + 2\mathring{r}\left[\operatorname{arctg}\frac{\mathring{\xi} - \mathring{r}\cos\varphi + \mathring{z} - \mathring{\zeta} + \mathring{a}}{\mathring{r}\sin\varphi}\right]\sin\varphi\right\}\Bigg|_0^{\mathring{\zeta}=\mathring{b}}\Bigg|_1^{\mathring{\xi}=\mathring{R}_н} d\varphi. \quad (11)$$

On the right side of (10), (11), the function with limits of integration (0, b, 1, R_H) is calculated the same as

$$f(\dot{\zeta}, \dot{\xi}, \dot{z}, \dot{r})\Big|_{0}^{\dot{\zeta}=\dot{b}}\Big|_{1}^{\dot{\xi}=\dot{R}_H} = f(\dot{b}, \dot{R}_H, \dot{z}, \dot{r}) - f(0, \dot{R}_H, \dot{z}, \dot{r}) - f(\dot{b}, 1, \dot{z}, \dot{r}) + f(0, 1, \dot{z}, \dot{r}).$$

The approximation of the experimental values of $\rho(B)$ for aluminum, beryllium [5, 6] and copper [3], as well as aluminum A999 of domestic production, is obtained according to (3) by the polynomial

$$\rho(B)\big|_{T=\text{const}} = \rho_0 + A_1 B^{1/4} + A_2 B^{1/3} + A_3 B^{1/2} + A_4 B^{2/3} + A_5 B + A_6 B^2 + A_7 B^3 + A_8 B^4. \quad (12)$$

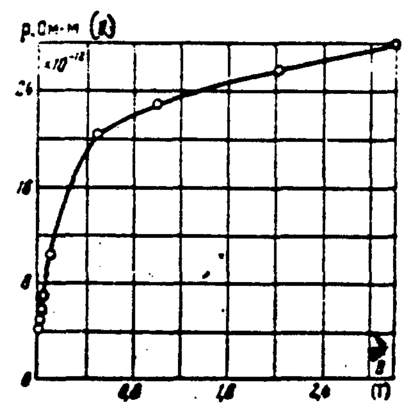

Fig. 1. KEY: (1) Ohms•m.

The form of the approximating polynomial (12), which corresponds to the nature of the experimental data, was established by preliminary calculations. The table gives the coefficients A_i calculated by the method of the least squares on a "Nairi-2" computer for aluminum, beryllium and copper at different temperatures. The deviation of the approximating dependences from the experimental values is 1-3%. Figure 1 shows the results of the experimental determination of

Table.

Материал (1)	(2) Алюминий [5,6]				(2) Алюминий A999	(3) Бериллий [5,6]			(4) Медь [3]
T (K)	4,2	20	25	30	4,2	4,2	20	77	[illegible]
	$\rho \cdot 10^{-12}$, Ом·м (5)								
A_i	5,0	23,1	30,0	54,7	4,12	200	200	1000	23.
$A_1 \cdot 10^{12}$	0,8809	−35,26	−277,7	−89,00	121,6	0	0	0	0
$A_2 \cdot 10^{12}$	4,021	66,99	662,4	36,02	−32,30	0	0	0	0
$A_3 \cdot 10^{12}$	−3,778	−27,17	−529,3	229,8	−355,3	0	0	0	0
$A_4 \cdot 10^{12}$	−10,86	−15,17	149,0	−269,8	399,8	0	0	0	0
$A_5 \cdot 10^{12}$	43,30	62,76	80,35	212,8	−140,6	1251	947,1	1504	[illegible]
$A_6 \cdot 10^{12}$	−18,52	−21,82	−43,77	−56,90	32,05	913,5	1074	468,7	[illegible]
$A_7 \cdot 10^{12}$	3,680	3,612	9,545	8,901	−6,852	0	0	0	[illegible]
$A_8 \cdot 10^{12}$	−0,2629	−0,2247	−0,7500	−0,5467	0,6594	0	0	0	0
B (T)	0—4				0—3	0—5			

(6) [1] Для меди 300 K/4,2 K = 70.

KEY: (1) Material. (2) Aluminum. (3) Beryllium. (4) Copper. (5) Ohms•m. (6) [1]For copper.

$\rho(B)$ for a short specimen of wire with a diameter of $1.93 \cdot 10^{-3}$ m made of aluminum A999 of domestic manufacture at a temperature of 4.5 K (the points in Fig. 1) and the approximating dependence (solid line) calculated according to (12) with the coefficients from the table.

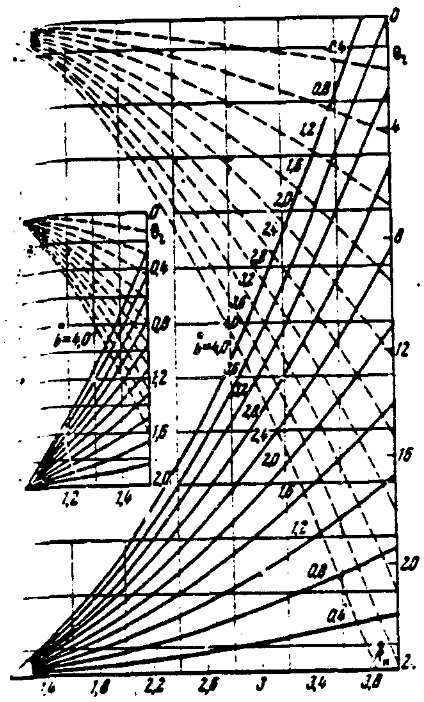

Fig. 2. Dependences of $\theta_1(\dot{R}_n)$ (solid lines) and $\theta_2(\dot{R}_n)$ (broken lines) on $\dot{b}$.

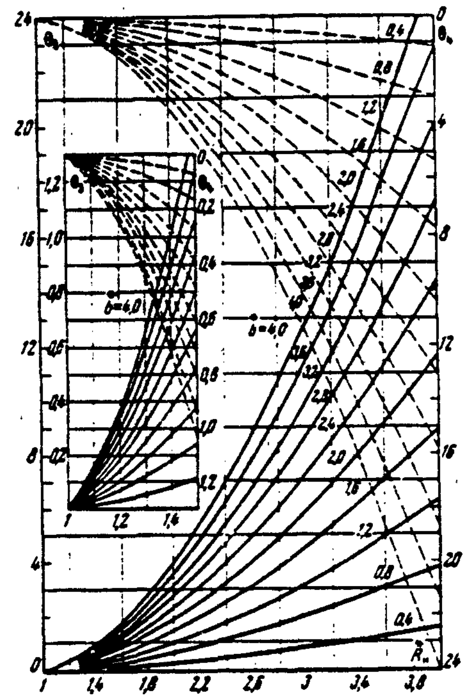

Fig. 3. Dependences of $\theta_1(\dot{R}_n)$ (solid lines) and $\theta_2(\dot{R}_n)$ (broken lines) on $\dot{b}$.

The integrals in (7), (10) and (11) were calculated by the Gaussian numerical method on a "Nairi-2" computer. It was established from the preliminary calculations that the required precision of the calculations of coefficients A_i with consideration of the possibilities of graphic plotting is provided by ten interpolation points in integrals (10), (11), and sixteen points (for each of the two symmetrical parts of the coil) in expression (7). The results of the numerical processing are given in Figures 2-5 in the form of the family of dependences of $\theta_i(\dot{R}_n)$ on $\dot{b}$.

Thus, the procedure for calculating the electrical losses and active resistance of a cryogenic inductor consists of the following: the coefficients A_i are taken from the table (or preliminary calculations) for the coil material according to the working temperature;

the coefficients θ_i are determined from the family of curves in Fig. 2 based on the assigned parameters of the inductor $\dot{R}_n, \dot{b}$; the calculation of the electrical losses P and resistance R is made using formulae (5), (6) according to the geometric dimensions of the inductor, the number of turns w, the current density j_m the pulse duty factor k_3 and the established values of A_i, θ .

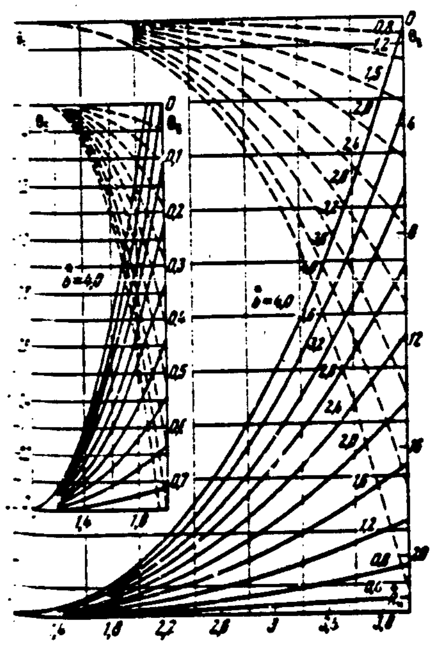

Fig. 4. Dependences of $\theta_5(\dot{R}_n)$ (solid lines) and $\theta_6(\dot{R}_n)$ (broken lines) on $\dot{b}$.

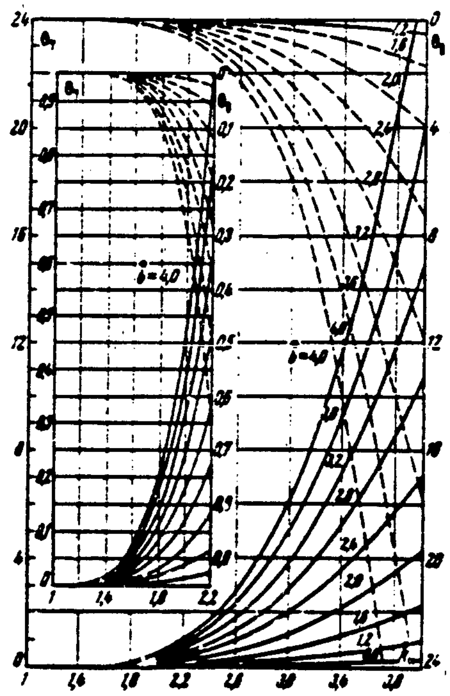

Fig. 5. Dependences of $\theta_7(\dot{R}_n)$ (solid lines) and $\theta_8(\dot{R}_n)$ (broken lines) on $\dot{b}$.

Because of the anticipated divergence of the experimental values of $\rho(B)$ for the same material, but different short specimens because of technological and other factors, it is recommended that the coefficients A_i of the polynomial (12) be determined in each specific case based on the experimental data. Along with the exponents v_i , the family of functions $\theta(\dot{R}_n)$, which depend on the relative geometry of the inductor, is universal.

As an illustration of the developed method, Fig. 6 gives the results of the experimental investigation[1] (the points in Fig. 6) and

[1]With the help of G. G. Svalov, the experimental points $\rho(B)$ and volt-ampere characteristic of the inductor were obtained by I. P. Radchenko, G. M. Sitnikova, and S. S. Salomakhin.

calculation (solid line) of a cryogenic solenoid made of aluminum wire (aluminum A999, Fig. 1 and table) with the parameters R_B = 1.1 cm, R_H = 3.56 cm ($\hat{R}_н = R_н/R_в = 3.24$), b = 4 cm ($b/R_B$ = $\hat{b}$ = 3.64), w = 124, $k_з \approx$ 0.37. The winding layers were separated by axial cooling channels ~1 mm high. The experiments were conducted in a cryostat with liquid helium ($T \approx$ 4.2 K). The difference in the calculated and experimental data can be explained by the instability of $\rho(B)$ over the length of the winding. According to Fig. 6, the effect of the natural magnetic field at a current of I = 350 A leads to approximately a six-fold increase in the resistance R and the losses P of the coil. The simplified top estimate of the effect of magnetoresistance in which ρ is considered to be constant for the entire coil and is determined from the dependence $\rho(B)$ based on the maximum induction B_{max} of the solenoid in the case in question at I = 350 A and $B_{max} \approx$ 0.96 T gives us a one and a half-fold increase in the resistance over the actual value.

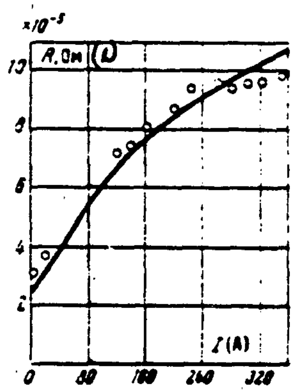

Fig. 6. KEY: (1) Ohms.

Conclusions. 1. The developed method of calculating the electrical losses and resistance of the winding of a cryogenic inductor with consideration of the magnetoresistance effect makes it possible to consider the effect of the magnetic field on the resistance of the coil and its losses.

2. The possibility of the approximation of the experimental dependence $\rho(B)$ by exponential polynomials of the form (12) with sufficient precision was shown.

3. The above method is recommended for use by engineers when designing cryogenic inductors.

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